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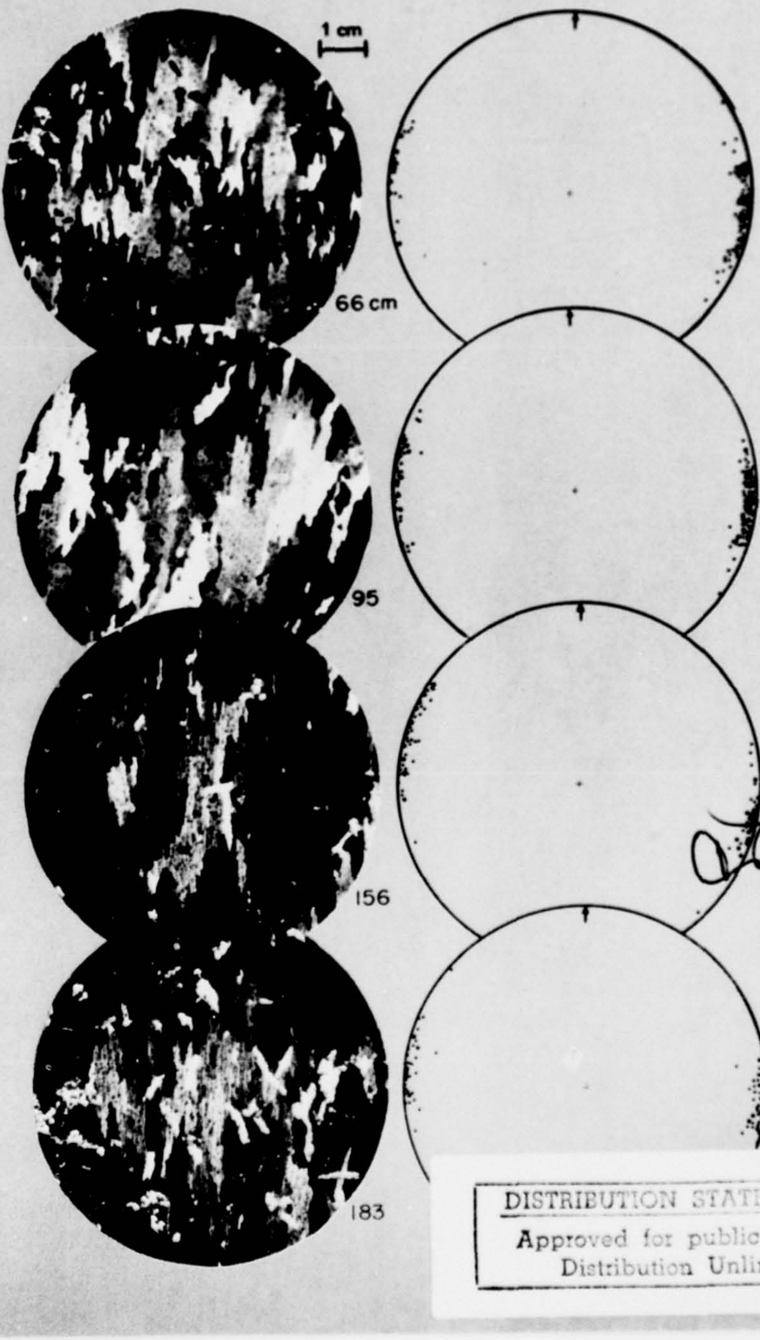

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The internal structure of fast ice near Narwhal Island, Beaufort Sea, Alaska

Anthony J. Gow and W.F. Weeks

October 1977

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Results of measurements of salinity, grain size, substructure dimensions and crystal fabrics of the undeformed 2.15-m-thick annual sea ice sheet near Narwhal Island, Alaska, are presented. A notable observation was the formation of a dominant c-axis horizontal structure in all ice below 14 cm, including transformation to a pronounced east-west alignment of the c-axes by a depth of 66 cm. This study confirms earlier reports of the occurrence of very strong horizontal c-axis alignments in arctic fast ice.

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PREFACE

This report was prepared by Dr. Anthony J. Gow, Geologist, and Dr. Wilford F. Weeks, Glaciologist, of the Snow and Ice Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory.

The field work upon which this study was based was carried out as part of Research Unit 88, *Dynamics of Near-Shore Ice*, and was supported by the Bureau of Land Management through interagency agreement with the National Oceanic and Atmospheric Administration as part of the Arctic Outer Continental Shelf Environmental Assessment Program.

The technical content of the report was reviewed by W.B. Tucker III, and Stephen F. Ackley of CRREL.

The authors would like to thank Austin Kovacs for bringing the work of Cherepanov to their attention.

CONTENTS

ILLUSTRATIONS

THE INTERNAL STRUCTURE OF FAST ICE NEAR NARWHAL ISLAND, BEAUFORT SEA, ALASKA

Anthony J. Gow and W.F. Weeks

INTRODUCTION

During recent studies of the large- and small-scale motions of the nearshore ice in the Beaufort Sea (Weeks et al. 1977), the opportunity was taken to examine the internal structure of the ice sheet itself. Field operations were centered around Narwhal Island, a barrier island located on the edge of the Arctic Ocean approximately 20 km north-northeast of Prudhoe Bay, Alaska. Pressing commitments to other parts of the ice dynamics program restricted examination of sea ice structure to just one location situated in fast ice about 200 m north of Narwhal Island (70°24'N, 147°32'W). However, the results of this investigation are considered sufficiently interesting to merit publication at this time.

SAMPLING AND ANALYTICAL PROCEDURES

Samples were obtained from large (1 m^2) blocks of ice harvested from a pit excavated to a depth of 1.5 m, and extended to a depth of 1.9 m (within 25 cm of the bottom) by core drilling. The azimuthal orientations of the ice blocks and the cores were carefully determined before removal. Errors in measurement of the aximuth were estimated not to exceed ± 3°. A total of 5 blocks and 5 bottom cores were harvested.

Gross structural features of the ice, such as banding and brine drainage channels, were examined using thick (1-cm) vertical slabs placed on a sheet of black flagging material and photographed in reflected sunlight. The bulk of the structural studies were performed using thin sections prepared in the field. Slices of ice measuring 10×10×1cm were frozen onto glass plates and sectioned on a microtome to a thickness of 0.3 to 1.0 mm, depending on the mean cross-sectional size of crystals in the ice. Prior to sectioning, it was usually necessary to freeze down the edges of the samples with fresh water to prevent them from slipping off the glass plates.

A Rigsby stage with a 10- ×12.5-cm press-type camera mounted above it was used to examine crystalline texture and fabrics in the thin sections of sea ice. In addition to providing a permanent record of texture, the thin section photographs were also used to measure crystal size variations and platelet spacings in the ice sheet. C (optic)-axis orientations were obtained entirely from measurements on horizontal thin sections. Sections from all bottom cores and from as many as 5 separate sections, selected randomly from the 1-m^2 area of the oriented ice block, were used to determine fabric patterns. A near-vertical orientation of brine platelets in the bulk of the ice further facilitated measurement of the c-axes, which in crystals of sea ice are always oriented perpendicular to the platelet structure.

RESULTS

Brine drainage features are best observed in vertical thick sections. Some typical examples from several different levels in the fast ice near Narwhal Island are given in Figure 1. Vertical channelization of brine drainage features is extensively developed. The same sections also reveal some horizontal banding, especially in the top 15 cm of ice (see also Fig. 3a). This banding, which is primarily associated with abrupt changes in the size and/or orientation of the crystals, is believed to be largely caused by variations in the growth rate of the sea ice. Except for these bands and a very distinctive bubble layer at 23-24 cm, banding was weakly developed in the ice examined. This is somewhat unusual as most previous observations have revealed widespread banded structure in arctic sea ice (e.g., Bennington 1963).

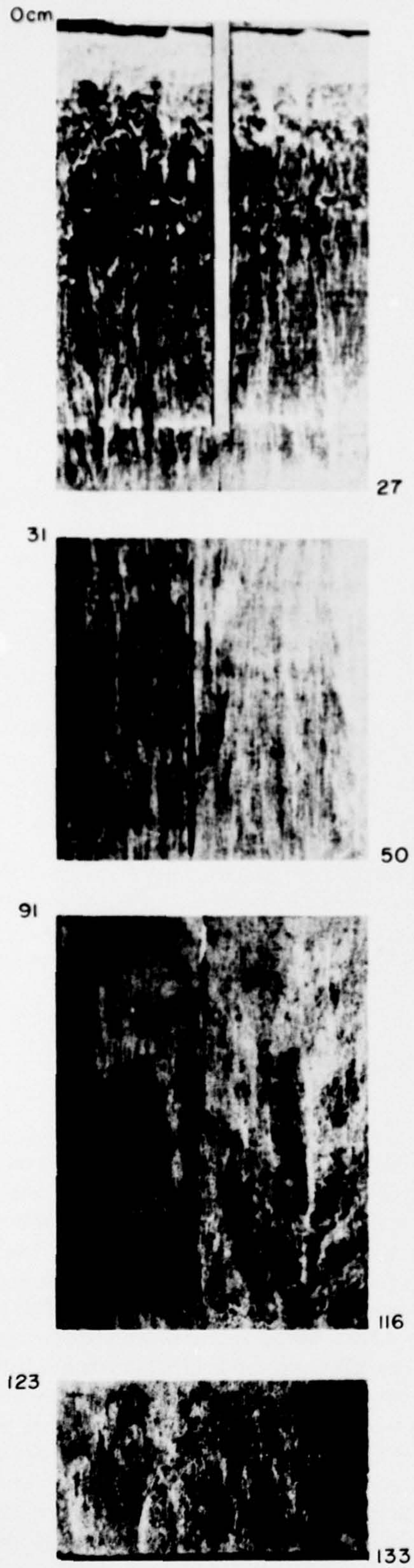

Figure 1. Brine drainage patterns in vertical sections of sea ice from Narwhal Island. Note also the faint banding in the two top sections and a distinctive layer of bubbles at 23-24 cm.

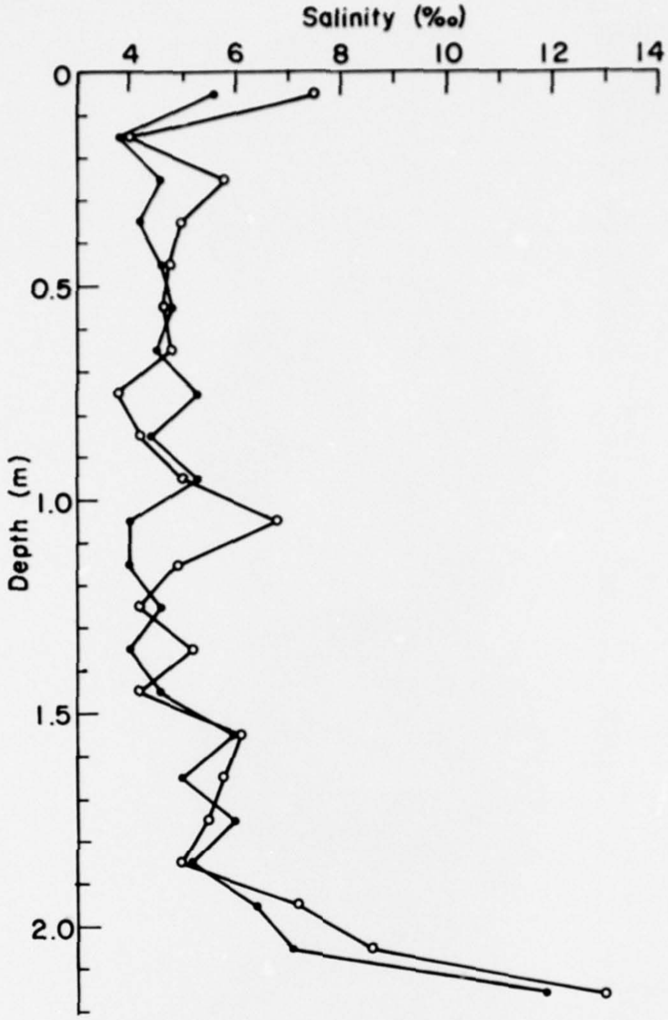

Figure 2. Ice salinity profiles from two cores drilled approximately 3 m apart, 18 April 1976, near Narwhal Island, Beaufort Sea, Alaska.

Salinity profiles from two ice cores drilled approximately 3 m apart are shown in Figure 2. These profiles are fairly typical for first-year ice of this thickness in that their only striking feature is the sharp increase in salinity in the lower portions of the profiles. The average salinity of the cores is slightly higher than values reported by Cox and Weeks (1974) for ice of the same thickness (5.5 ‰ as opposed to 4.4 ‰).

A vertical thin section profile demonstrating crystal texture and fabric variations in the top 30 cm at Narwhal Island is shown in Figure 3a. This 30-cm section contains all the major transitions in texture, most of which actually occur within the top 13-14 cm of ice. This region corresponds to the so-called transition zone of Perey and Pounder (1958). The banded nature of the ice in this transition zone is also clearly delineated by distinctive changes in the textural characteristics of the crystals. These transitions, which are also associated with distinctive changes in crystal fabrics, can be summarized as follows:

1. The topmost layer, extending from the surface to 3.5-cm depth, is very bubbly and fine-grained (cross-sectional dimensions of crystals generally less than 2 mm) and is composed of crystals with randomly oriented c-axes. Although this layer originated either as slush ice or as infiltrated snow ice, its exact origin could not

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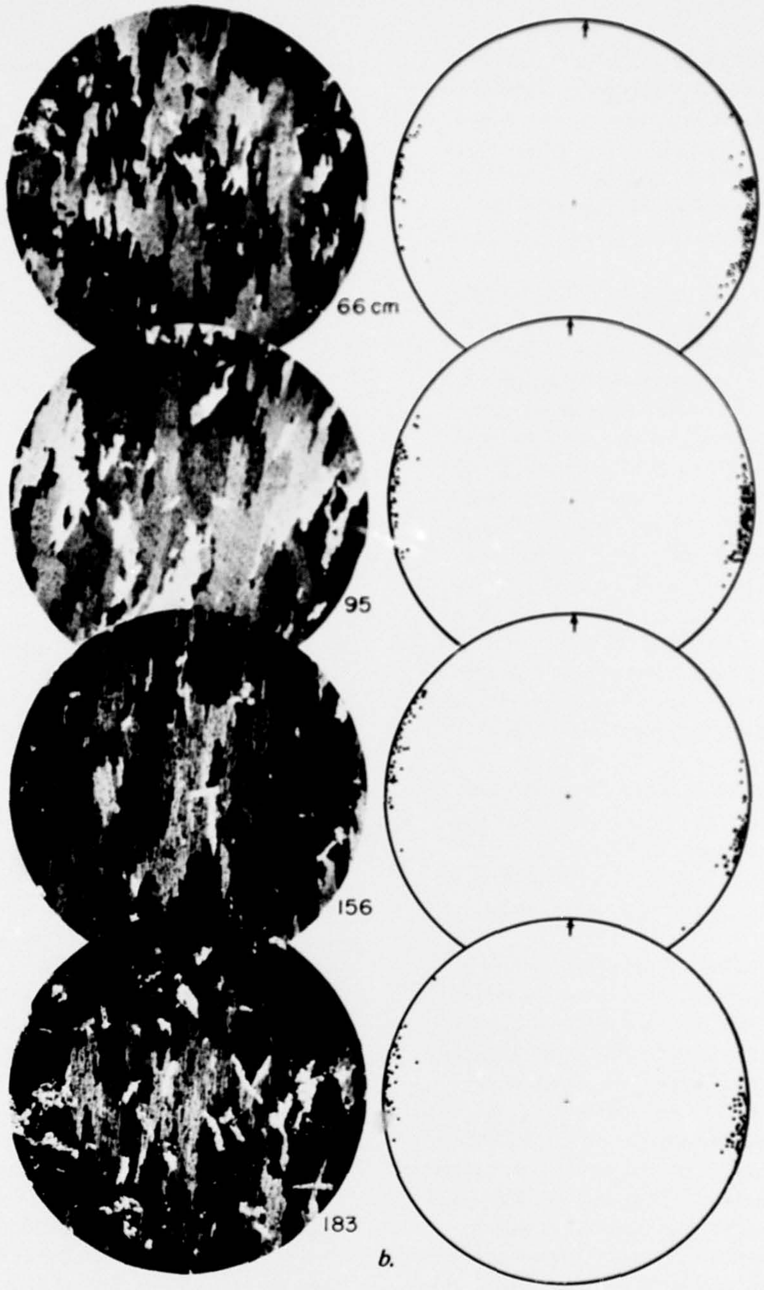

Figure 3. Crystal textures and fabrics of sea ice near Narwhal Island, Beaufort Sea, Alaska. Textures photographed between crossed polaroids. a) contains continuous vertical section from surface to 30 cm. All other photographs in a and b obtained from horizontal thin sections; scale as indicated in section from 3 cm. Note intermixing of tabular crystals (vertical c-axes) and columnar crystals (horizontal c-axes) at 5 and 8 cm. The large dots in the fabric diagrams indicate the largest crystals present in the thin sections. The c-axes of these crystals tend to be more tightly clustered than those of the smaller crystals. This may indicate that the large crystals have grown at the expense of the less strongly oriented smaller crystals. Arrows at the top of each fabric diagram indicate the direction of true north.

be evaluated from salinity measurements. Oxygen isotope ($^{18}O/^{16}O$) analyses (though not performed in this instance) would almost certainly have resolved this question of origin, since snow ice, being derived largely from atmospheric material (snow), would be appreciably more depleted in ^{18}O than slush ice formed substantially from direct crystallization in sea water.

2. The next layer, extending from 3.5 to 8 cm, includes in its upper part large tabular crystals up to 3 cm in diameter (indicated by the open circles) that show a mosaic texture and have predominantly c-axis vertical orientation. At a depth of about 4.5 cm, these large mosaic crystals become intermixed with columnar crystals exhibiting mainly horizontal c-axes. This is clearly demonstrated in the fabric pattern at 5-cm depth. By a depth of 8 cm, only a few remnant c-axis vertical crystals remain. Some fine banding, indicative possibly of reversals in crystal fabric, was observed between 8 and 13 cm. Vertical brine drainage is less extensively developed in this region than above or below it. A rapid transformation to a totally elongate-prismatic crystal texture which has occurred by about 14 cm appears to mark the end of the transition zone.

3. At a depth of 14 cm, the fast ice at Narwhal Island is composed completely of crystals with their c-axes oriented substantially within the horizontal plane of the ice sheet. However, the distribution of c-axes within the horizontal plane appears to be essentially random.

4. Vertical thin sections show that below the transition zone individual crystals extend downwards for 10 cm or more (some probably extend completely to the bottom of the ice sheet). The largest crystal diameters occur immediately below the transition zone (that is 14 to 30 cm below the upper surface of the ice sheet) where maximum cross-sectional dimensions occasionally reach 5 cm. In general, cross-sectional dimensions do not exceed 2-3 cm, and although small fluctuations in mean diameter do occur at several levels, no really systematic changes in crystal size were observed in the lower two-thirds of the ice sheet. However, as seen in horizontal sections, crystals do tend to be elongated in the direction normal to the c-axis (parallel to the plane of the plate-like substructure). A similar elongation has been noted in a study of sea ice at Barrow, Alaska (Weeks and Hamilton 1962).

5. As the fabric pattern at 26 cm clearly illustrates, ice crystals at this depth within the ice sheet no longer have their c-axes randomly distributed within the horizontal plane. A preferred orientation of c-axes (approximately east-west) is firmly established by 66 cm (Fig. 3b) and this orientation is maintained to a depth of at least 183 cm. As indicated in the caption of Figure 3, the larger crystals tend to be more strongly oriented than the smaller crystals in the same section. Crystal fabric measurements were terminated at 183 cm because of a lack of suitably oriented samples from the deeper ice. However, the near-parallel arrangement of platelike crystals observed in cores from a hole that penetrated the bottom ice would indicate that this azimuthal alignment of crystallographic c-axes also extends to the bottom of the fast ice at Narwhal Island.

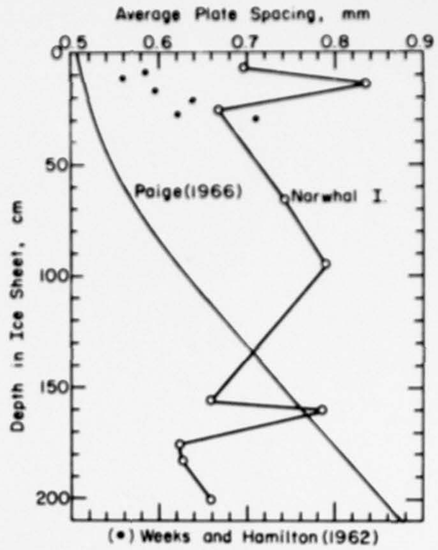

Figure 4. Subcrystal plate width versus depth of ice at Narwhal Island. Curve (Paige 1966) was generalized from profiles obtained from several different locations in McMurdo Sound, Antarctica.

The only aspect of sea ice substructure that might be systematically related to the freezing velocity of sea water is the so-called plate width, as determined from the spacing (measured parallel to the c-axis) between adjacent brine layers trapped in the crystals of ice. In this context each single crystal of sea ice may be considered as a packet of plates separated one from another by arrays of brine pockets. Weeks and Hamilton (1962) reported a generally linear increase in average plate width with depth in 30-cm-thick sea ice at Point Barrow, Alaska. Paige (1966) also observed a progressive increase in plate width in 3-m-thick ice in McMurdo Sound, Antarctica. Both sets of data are reasonably compatible with the observations made on NaCl ice by Lofgren and Weeks (1969) which indicated that plate width

increases as growth velocity decreases coupled with the fact that in general growth velocity would be expected to decrease with increasing thickness of ice.

However, as indicated in Figure 4, no such systematic increase in plate spacing is observed in fast ice at Narwhal Island where plate width appears to fluctuate about a mean value of 0.7 mm and actually decreases in the lower part of the ice sheet. These data might indicate a fluctuating pattern of ice growth at Narwhal Island, including an increase in growth velocity near the bottom. However, this latter behavior would be exceptional considering the thickness of the ice sheet and its insulating nature. Relating the various elements of substructure to the growth history of thick sea ice is of more than academic interest since the mechanical properties of sea ice, especially its strength, are known to vary with position in the ice sheet. Some of this variation must depend in part on both the plate spacing and the degree of alignment of the plates.

DISCUSSION

The authors are fully aware that their observations have only shown that, in the lower 1.50 m of 2.15-m-thick first-year ice at one site north of Narwhal Island, the sea ice crystals are all oriented so that their c-axes are within a few degrees of each other in the horizontal plane. The exact size of the area of ice that has the same (east-west) crystal orientation is not known, only that the area is larger than 1 m^2.

Peyton (1963, 1966), Smith (1964) and Cherepanov (1971) among others have also reported instances of a strong axial alignment of c-axes in arctic sea ice. According to Smith (1964), old sea ice incorporated into ice island Arlis II may exhibit near perfect alignment of the c-axes over areas as large as 10 m on a side. Peyton (1966) reports examining a 3×3-m block of 1.6-m-thick sea ice and finding that the bottom meter exhibited a constant c-axis orientation over the entire 9-m^2 cross section. Whether or not these large areas are composed of a single crystal of ice is not made entirely clear, but this certainly is not the case at Narwhal Island where individual crystals (even those of closely matching orientation) can easily be delineated under crossed polaroids. Indirect evidence of the existence of more extensive areas of near-perfect crystal alignment is reported by Campbell and Orange (1974), who suggest, from studies of the electrical properties of ice in the Canadian Arctic, that oriented crystal structure may extend over distances on the order of kilometers.

Perhaps the most remarkable report of preferred c-axis alignments in sea ice is that of Cherepanov (1971), who observed conditions of near-constant crystal orientation over areas of hundreds of square kilometers in the Kara Sea. He observed two principal directions of spatial alignment of crystals. He suggested that these preferred crystal orientations may have been due to the influence of the earth's magnetic field either directly or by a coupling with the potential difference that is known to be established between the liquid and solid phases during freezing. No details were given as to how this coupling might work, or why a nonferromagnetic substance like ice should react so strongly to the earth's magnetic field.

CONCLUSIONS

Measurements of salinity, grain size, substructure dimensions and crystal orientation were obtained on a large 1- x 1-m block of undeformed 2.15-m-thick first-year sea ice near Narwhal Island, Beaufort Sea, Alaska. Crystallographic studies show a dominant c-axis horizontal structure in all ice below 14 cm including transformation to a pronounced east-west alignment of the c-axes by a depth of 66 cm. Although the maximum cross-sectional dimensions of crystals do not generally exceed 2 to 3 cm, the degree of crystal alignment is undoubtedly sufficient to cause significant changes in the properties of the ice with changes in direction.

The areal extent of oriented crystal structure in fast ice near Narwhal Island cannot be determined from studies at a single location. However, the published observations of several other investigators lead us to believe that the development of oriented domains in sea ice is common and that the domain size may be very large (tens or even hundreds of square kilometers). If such strong ice fabrics are typical at near coastal locations, it will prove necessary to take this factor into account in the design of offshore structures for ice covered waters. For instance, the "hard fail" compressive strength of sea ice is approximately 3 times the "easy fail" strength (Peyton 1966). Also, recent studies of Martin (1977) indicate that such "oriented" ice is highly effective in entrapping spilt crude oil.

Follow-up studies of preferred crystal orientations in the fast ice in the general vicinity of Narwhal Island have just been completed. Preliminary analysis of the field data now suggests that the dominant direction of crystal alignment at any location is controlled by the long-term mean current direction at the ice/water interface.

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